

Axino as Cold Dark Matter Candidate

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Abstract. The possibility of the CDM axino is presented. From the early days of supersymmetry, axino has been considered as hot dark matter and warm dark matter. But the CDM axino has been considered quite recently. It is because the low reheating temperature of the universe is gaining momentum recently from various considerations in particle cosmology. I present a general introduction on the CDM's, in particular the axino, the calculation on the axino density in the universe, and the constraints imposed on the axino parameters.

1 Introduction

In this talk, I review the work collaborated with Covi *et al.* [1,2] on the possibility of the CDM axino.

Modern cosmology needs dark matter and dark energy in the universe: $\Omega_{\text{CDM}} \simeq 0.3$, $\Omega_A \simeq 0.65$. There are several particle candidates for the CDM: heavy neutrino in the GeV range, axion in the 10^{-5} eV range, the lightest superpartner(LSP) in the 100 GeV range, wimpzilla in the 10^{12} GeV range, axino, and other hypothetical heavy particles.

The particle mass and the interaction strength are provided by particle physics. In the standard Big Bang cosmology, this information leads to the decoupling temperature(T_D) below which the number of particles in the comoving volume is preserved. But the needed inflationary period reheats the universe, after a period of supercooling, to the reheating temperature T_R . If $T_D > T_R$, the particles are mostly diluted out and the first guess on its number density is that it cannot serve as dark matter(DM). But even after the reheating phase, the thermal production can be effective enough to create sufficient number of heavy particles to close the universe. It has been most extensively studied for the case of O(100 GeV) gravitino[3]. Because of the gravitino problem, we consider the reheating temperature below 10^9 GeV.¹

For $T_D < T_R$, the DM candidates are

- Neutrinos: G_F is the interaction strength.
- LSP: $\frac{1}{M_{\text{SUSY}}^2}$ is the interaction strength.

For $T_D > T_R$, the DM candidates are

¹ For the wimpzilla case, the exit phase of the inflation produce the required density.

- Axion: $\frac{1}{F_a}$ is the interaction strength. Collective motion of axions below the QCD phase transition contributes.
- Axino: $\frac{1}{F_a}$ is the interaction strength. Thermal and nonthermal productions contribute.

2 Axion and gravitino constraints

Before discussing the axino CDM possibility, let us briefly review the cold axions, collectively moving in the universe. The basic difference of the axion candidate from the other ones is that axion is boson and it is possible to have a collective motion. The classical axion potential is extremely flat due to the very tiny invisible axion mass[4]. Because of the extremely weak interaction strength, the axion vacuum stays at a point $\langle a \rangle$ for a long time. The vacuum starts to oscillate when the Hubble time ($\sim 1/H$) is larger than the oscillation period ($1/m_a$), $H < m_a$ which occurs when the temperature is about 1 GeV[5]. We understand that the axion is the pseudo-scalar field, having the interaction only through the anomaly

$$\frac{1}{32\pi^2} \frac{a}{F_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv \frac{a}{F_a} \{F\tilde{F}\} \quad (1)$$

where $\tilde{F}_{\mu\nu}$ is the dual field strength $(1/2)\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$. We stress that there should not exist any other term in the axion potential. This kind of nonrenormalizable interaction can arise in several different ways:

- From fundamental interaction such as in superstring[6]: $F_a \sim$ Planck mass.
- From composite models[7]: $F_a \sim$ compositeness scale.
- From renormalizable theories[8]: A global symmetry can have a gluon anomaly. If this global symmetry is spontaneously broken, there arises a Goldstone boson coupling to the gluon anomaly. $F_a \sim$ the global symmetry breaking scale.

Then the current axion energy density is estimated to be[9]

$$\rho_a(T_\gamma) = m_a(T_\gamma)n_a(T_\gamma) \simeq 2.5 \frac{F_a}{M_P} \frac{F_a m_a}{T_1} T_\gamma^3 \left(\frac{A(T_1)}{F_a} \right)^2. \quad (2)$$

If F_a is large ($> 10^{12}$ GeV), the axion energy dominates the current energy density in the universe. Since the energy density is proportional to the number density, it behaves like a CDM. On the other hand, if F_a is small then the axion interaction is relatively strong and too much axions are produced in the core of stars. SN1987A restricts its lower bound around 10^9 GeV, leading to the axion window

$$10^9 \text{ GeV} < F_a < 10^{12} \text{ GeV}. \quad (3)$$

The gravitino produced thermally after inflation decays very late in the cosmic time scale ($> 10^3$ s), and can dissociate the light nuclei by its decay

products[10]. Inflation was used to dilute the primordial gravitinos, but thermal production of gravitinos are troublesome in cosmology if it exceeds[3]

$$T_R > 10^9 \text{ GeV.} \quad (4)$$

Therefore, in supersymmetric theories we must consider relatively small reheating temperature after inflation.

3 Axino

Therefore, in supersymmetric extension of the axion model, axion can be a CDM candidate but it is produced very late. Its supersymmetric partner is axino, and the reheating temperature T_R must be smaller than T_D . The axion a and axino \tilde{a} are gathered in a supermultiplet,

$$\Phi = \frac{1}{\sqrt{2}}(s + ia) + \sqrt{2}\tilde{a}\theta + F_\Phi\theta\theta \quad (5)$$

where s is the scalar partner of axion, the saxion. The axion couples to the gluon anomaly through $(1/F_a)\{F\tilde{F}\}$. It is known that the potential arising from this gluon interaction settles $\langle a \rangle$ at zero, which is the Peccei-Quinn mechanism.

For axino to be CDM, it must be stable or practically stable. Without the R -parity conservation, this cannot happen. Thus, we require a practical R -parity conservation. For axino to be the LSP, it must be lighter than the lightest neutralino whose mass is expected to be around 100 GeV. Thus, an estimate of the axino mass is of prime importance for a CDM axino. Note that there is no theoretical upper bound on the axino mass.

Since axion is almost massless, one might expect that the axino and saxion are almost massless in the first approximation. However, the saxion obtains a soft mass term below SUSY breaking scale. It is like the SM SUSY scalars. So the axino mass is intimately related to the SUSY breaking scenario also. Actually, it is known that the axino obtains a substantial mass[11]. For a specific model, including the soft SUSY breaking terms, consider

$$V = |f|^2(|S_1|^2 + |S_2|^2)|Z|^2 + (A_1 f S_1 S_2 Z - A_2 f F_a^2 Z + \text{h.c.}) \quad (6)$$

where Z, S_1 , and S_2 are the SM singlets, and the supersymmetric term comes from the superpotential $W = fZ(S_1 S_2 - F_a^2)$. Since $\langle S_i \rangle$ is of order F_a , Z is of order the A term. Thus, the fermionic partners have the mass matrix of the form,

$$\begin{pmatrix} S_1 \\ S_2 \\ Z \end{pmatrix} \begin{pmatrix} 0 & m_{\tilde{a}} & fF_a \\ m_{\tilde{a}} & 0 & fF_a \\ fF_a & fF_a & 0 \end{pmatrix} \quad (7)$$

where $m_{\tilde{a}} = f\langle Z \rangle$. One eigenvalue is the axino mass $\sim m_{\tilde{a}}$, and the other masses are of order F_a . As seen from this example, the axino mass is basically a free parameter, but is expected to be somewhat smaller than the naive SUSY

breaking scale due to the coupling f [12]. But in some models, the axino mass can be much smaller than the SUSY breaking scale. Take a superpotential $W' = fZ(S_1S_2 - X^2) + (\lambda/3)(X - M)^3$ with one more singlet X which carries a vanishing PQ charge. This superpotential is much more complicated to analyze, but still we can show that $m_{\tilde{a}} = O(A - 2B + C) + O(m_{3/2}^2/F_a)$. For the standard pattern of soft terms, $B = A - m_{3/2}$, $C = A - 2m_{3/2}$. Then, the axino mass is of order keV. Thus, even the tree level axino mass needs the knowledge on the full superpotential[13]. Therefore, we can consider the axino mass a free parameter, and we restrict our discussion in the region where axino is the LSP, which is the most probable choice with the PQ symmetry.

The universal axion coupling is to the anomaly term. Therefore, the axino coupling to the gauge multiplet is the most important couplings. For the fermions, only the coupling to the top quark is important. We consider all these couplings when they become appropriate.

4 Axino density in the universe

The axino decoupling temperature is

$$T_D \simeq 10^{10} \text{ GeV} \left(\frac{F_{a,11}}{N_{DW}} \right) \left(\frac{0.1}{\alpha_s} \right)^3 \quad (8)$$

where N_{DW} is the domain wall number in axion models and $F_{a,11}$ is the axion decay constant in units of 10^{11} GeV. For $T_D < T_R$, at T_D the number density is determined. For axinos not to close the universe, it should not exceed 12.8 eV $g_*(T_D)/g_{eff}$ where $g_* = 915/4$, $g_{eff} = 1.5$, which was used for the $O(< 2 \text{ keV})$ warm DM axino by Rajagopal *et al.*[14]. But in our $T_R < T_D$ case, due to the gravitino problem[3], we do not consider this region seriously. On the other hand, we can consider much heavier axinos. The estimation of the axino density in the universe is considered for the thermal case and for the non-thermal case(by the neutralino decay).

For the thermal production, we solve the Boltzmann equation,

$$\frac{dn_{\tilde{a}}}{dt} = \sum_{i,j} \langle \sigma(i + j \rightarrow \tilde{a} + \dots) v_{rel} \rangle n_i n_j + \sum_i \langle \Gamma(i \rightarrow \tilde{a} + \dots) \rangle n_i. \quad (9)$$

The axino yield, the number density divided by the entropy $s = (2\pi^2/45)g_{s*}T^3$, is split into two pieces one from the scattering process and the other by the decay, $Y_{\tilde{a}}^{TP} = \sum_{i,j} Y_{i,j}^{scatt} + \sum_i Y_i^{dec}$ where

$$Y_{i,j}^{scatt} = \int_0^{T_R} dT \frac{\langle \sigma(i + j \rightarrow \tilde{a} + \dots) \rangle n_i n_j}{sHT}, \quad Y_i^{dec} = \int_0^{T_R} dT \frac{\langle \Gamma(i \rightarrow \tilde{a} + \dots) \rangle n_i}{sHT}.$$

For the scattering, we consider ten important processes shown in Table 1. On the other hand, the non-thermal production is basically by the decay process of the very long lived neutralino[1]. These contributions are shown in Fig. 1. For a

Table 1. The cross sections for the different axino thermal production channels involving strong interactions. Masses are neglected except for the plasmon mass m_{eff} .

n	Process	$\overline{\sigma}_N$	n_{spin}	n_F	$\eta_1\eta_2$
A	$g^a + g^b \rightarrow \tilde{a} + \tilde{g}^c$	$\frac{1}{8} f_{abc} ^2$	4	1	1
B	$g^a + \tilde{g}^b \rightarrow \tilde{a} + g^c$	$\frac{5}{16} f_{abc} ^2[\ln(s/m_{eff}^2) - \frac{15}{8}]$	4	1	$\frac{3}{4}$
C	$g^a + \tilde{q}_k \rightarrow \tilde{a} + q_j$	$\frac{1}{8} T_{jk}^a ^2$	2	$N_F \times 2$	1
D	$g^a + q_k \rightarrow \tilde{a} + \tilde{q}_j$	$\frac{1}{32} T_{jk}^a ^2$	4	$N_F \times 2$	$\frac{3}{4}$
E	$\tilde{q}_j + q_k \rightarrow \tilde{a} + g^a$	$\frac{1}{16} T_{jk}^a ^2$	2	$N_F \times 2$	$\frac{3}{4}$
F	$\tilde{g}^a + \tilde{g}^b \rightarrow \tilde{a} + \tilde{g}^c$	$\frac{1}{2} f_{abc} ^2[\ln(s/m_{eff}^2) - \frac{29}{12}]$	4	1	$\frac{3}{4} \frac{3}{4}$
G	$\tilde{g}^a + q_k \rightarrow \tilde{a} + q_j$	$\frac{1}{4} T_{jk}^a ^2[\ln(s/m_{eff}^2) - 2]$	4	N_F	$\frac{3}{4} \frac{3}{4}$
H	$\tilde{g}^a + \tilde{q}_k \rightarrow \tilde{a} + \tilde{q}_j$	$\frac{1}{4} T_{jk}^a ^2[\ln(s/m_{eff}^2) - \frac{15}{8}]$	2	$N_F \times 2$	$\frac{3}{4}$
I	$q_j + \tilde{q}_k \rightarrow \tilde{a} + \tilde{g}^a$	$\frac{1}{24} T_{jk}^a ^2$	4	N_F	$\frac{3}{4} \frac{3}{4}$
J	$\tilde{q}_j + \tilde{q}_k \rightarrow \tilde{a} + \tilde{g}^a$	$\frac{1}{24} T_{jk}^a ^2$	1	$N_F \times 2$	1

low reheating temperature, the thermal production is not effective. In Fig. 1, the bulge at the lower left corner is the non-thermal production. In Fig. 1, we show for $F_a = 10^{11}$ GeV so that the cold axions are not the dominant component of CDM.

For the calculation of the non-thermal production, we consider LOSP and NLSP where LOSP is the lightest superpartner among ordinary SM particles and NLSP is the next-to-LSP or the second lightest superpartner. It is most likely that the LOSP is the lightest bino-like neutralino and NLSP can be LOSP or gravitino or something else. For a bino-like LOSP χ , the decoupling temperature of the LOSP is $T_D \simeq m_\chi/20$. At $T < T_D$ and $\Gamma_\chi \ll H$, the LOSP decays during the radiation dominated era to produce axinos through $\chi \rightarrow \tilde{a} + \gamma$ to yield[2]

$$Y_\chi(T) \simeq Y_\chi^{EQ}(T_D) \exp\left(-\int_T^{T_D} \frac{dT'}{T'^3} \frac{m_\chi^3 \langle \Gamma_\chi \rangle_{T'}}{H(m_\chi)}\right). \quad (10)$$

Therefore, we have a simple expression,

$$\Omega_{\tilde{a}} = \frac{m_{\tilde{a}}}{m_\chi} \Omega_\chi. \quad (11)$$

The neutralino decays at the cosmic time

$$\tau(\chi \rightarrow \tilde{\gamma}) = 0.33 \text{ s} \frac{1}{C_{aYY}^2 Z_{11}^2} \left(\frac{1/128}{\alpha_{em}^2}\right)^2 \left(\frac{F_a/N_{DW}}{10^{11} \text{ GeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_\chi}\right)^3 \left(1 - \frac{m_{\tilde{a}}^2}{m_\chi^2}\right)^{-3}$$

Depending on the models, the decay modes can be different. If there are more channels for the χ decay, then it will give an even more efficient implementation of the non-thermal production of axino through the neutralino decay.

5 Constraints

We must impose the conditions that (1) not too much axino energy density at the time of Big Bang nucleosynthesis(BBN), (2) the BBN not spoiled by χ decay producing the SM particles, and (3) axinos becoming cold before the galaxy formation era.

Note in passing that if $m_{\tilde{a}} < m_{3/2} < m_\chi$, i.e. for the gravitino NLSP then the gravitino problem disappears since it decays to axion and axino[15]. On the other hand, if χ is the NLSP, the gravitino problem is present[3]. In this case, the non-thermally produced axinos are estimated to give Eq. (11). In Fig. 2, we include all these constraints and plot the restriction on the reheating temperature versus axino mass. This figure is not changed even if there is no gravitino problem because of the gravitino NLSP. The shaded region is where the axino can be a CDM possibility. This happens O(GeV) axino.

Note that for a high reheating temperature the thermal production contribution dominates. In the figure, there is the solid line denoting the critical energy density by axinos. Even if the reheating temperature is below the critical energy density line, there still exists a axino CDM possibility by non-thermally produced axinos[1]. Note that non-thermally produced axinos can be CDM for relatively low reheating temperature(< 10 TeV) for which axino mass should be

$$10 \text{ MeV} < m_{\tilde{a}} < m_\chi \quad : \quad \text{non - thermal axinos as CDM possibility} \quad (12)$$

The shaded region corresponds to the MSSM models with the constraint $\Omega_\chi h^2 < 10^4$ but still allowable axino energy density. One can choose 30 % CDM in this region. However, if we restrict further that all SUSY mass parameters are below 1 TeV, then we have $\Omega_\chi h^2 < 10^2$. For a sufficient axino energy density for the axino CDM, then we have

$$m_{\tilde{a}} \geq 1 \text{ GeV} \quad (13)$$

but less than the neutralino mass.

6 Detection possibility of CDM axino

If R -parity is exact, then the CDM axino cannot decay, and there is no way to prove the CDM axino possibility. If there is any chance to prove the CDM axino by observation, then the axino must decay[16]. For it to constitute most of CDM in the universe, its lifetime must be of order the age of the universe. Since it is assumed to be the LSP, the R -parity must be feebly broken. Then the CDM axino can decay.

For the simplicity of discussion, let us consider the bilinear terms only

$$W = \mu_\alpha L_\alpha H_2 \quad (14)$$

where $\alpha(= 1, 2, 3)$ is the flavor index, $\mu_\alpha = O(\text{eV})$ is the constraint from the neutrino mass bound. This bound applies to the heaviest neutrino, presumably ν_τ . In this case μ_3 is bounded as

$$|\mu_3| \leq M_{\tilde{H}_2, T_{eV}}^{1/2} \text{ MeV}. \quad (15)$$

With the R -parity violation, we expect the decays

$$\begin{aligned}\tilde{a} &\rightarrow \nu + \gamma (\text{or } l^+ l^-), \\ \tilde{a} &\rightarrow \nu + a \\ \tilde{a} &\rightarrow \tau^+ + \pi^-.\end{aligned}\tag{16}$$

In fact, the $\nu\gamma$ mode is most important in cosmology. For the cosmic importance of the decay, we need to know the lifetime. Let us try phenomenological Lagrangians,

$$\epsilon_0 \phi \tilde{a} \psi, \quad i\epsilon_1 \frac{\alpha_{em}}{F_a} F^{\mu\nu} \tilde{a} \gamma_5 [\gamma_\mu, \gamma_\nu] \psi,\tag{17}$$

for the final pseudo-scalar and photon, respectively. Then, for each case the lifetime can be estimated. In particular, to the photon mode

$$\tau_{\tilde{a}} = \frac{4 \times 10^4}{\epsilon_1^2} n_\psi m_{\tilde{a}, GeV}^{-3} F_{a,12}^2 P_1^{-1} [\text{s}]\tag{18}$$

where P_1 is the phase space factor. ϵ_1 is known if the R -parity violation is given. Since the most stringent bound comes from the diffuse gamma ray, we focus on this mode. The observed gamma ray flux is

$$\frac{F_\gamma}{d\Omega} \leq (10^{-3} - 10^{-5}) E_{GeV}^{-1} \text{cm}^{-2} \text{sr}^{-1} [\text{s}^{-1}].\tag{19}$$

If $t_{rec} < \tau_{\tilde{a}} < t_0$ where t_0 is the age of the universe, most axinos have decayed by now and the flux has a peak at $E_0 = (m_{\tilde{a}}/2)(\tau_{\tilde{a}}/t_0)^{2/3}$. Since the photons from axino decay should not exceed the observed flux, we obtain

$$\tau_{\tilde{a}} < 10^{-10} t_0 \Omega_a^{3/2} h^3\tag{20}$$

which is in conflict with $\tau_{\tilde{a}} > t_{rec} \sim 10^{13}$ s.

If $\tau_{\tilde{a}} > t_0$, a similar consideration gives the axino lifetime larger than $4 \times 10^{24-26} \Omega_a h$ s. This translates to the μ_3 bound,

$$\mu_3 < 10^{2-3} \text{ eV}.\tag{21}$$

If μ_3 in (21) is taken, the idea of neutrino mass generation by R -parity violation is not enough. Thus, the unstable CDM axino is not viable with the neutrino mass generation by R -parity violation. Still, the CDM axino decay can be detected if the parameters lie in the region given above.

7 Conclusion

In conclusion, we discussed

- Supersymmetry is the solution of the gauge hierarchy problem, and the PQ symmetry with a very light axion with $10^9 \text{ GeV} < F_a < 10^{12} \text{ GeV}$ is the solution of the strong CP problem. This leads to the axino which can be the LSP.

- The gravitino problem must be considered in this case, with $T_R < 10^9$ GeV.
- Due to the much more stronger axino production than the gravitino production, T_R must be much smaller than the one given by the gravitino consideration. It can be in a multi TeV region.
- Thermal and nonthermal production of axinos are possible. In this case, O(GeV) axino CDM possibility exists.
- Finally, the attempt to explain the neutrino mass via the R -parity violation mechanism is inconsistent with the CDM axino. However, in this case there is a room for the detection of axino decay debris.

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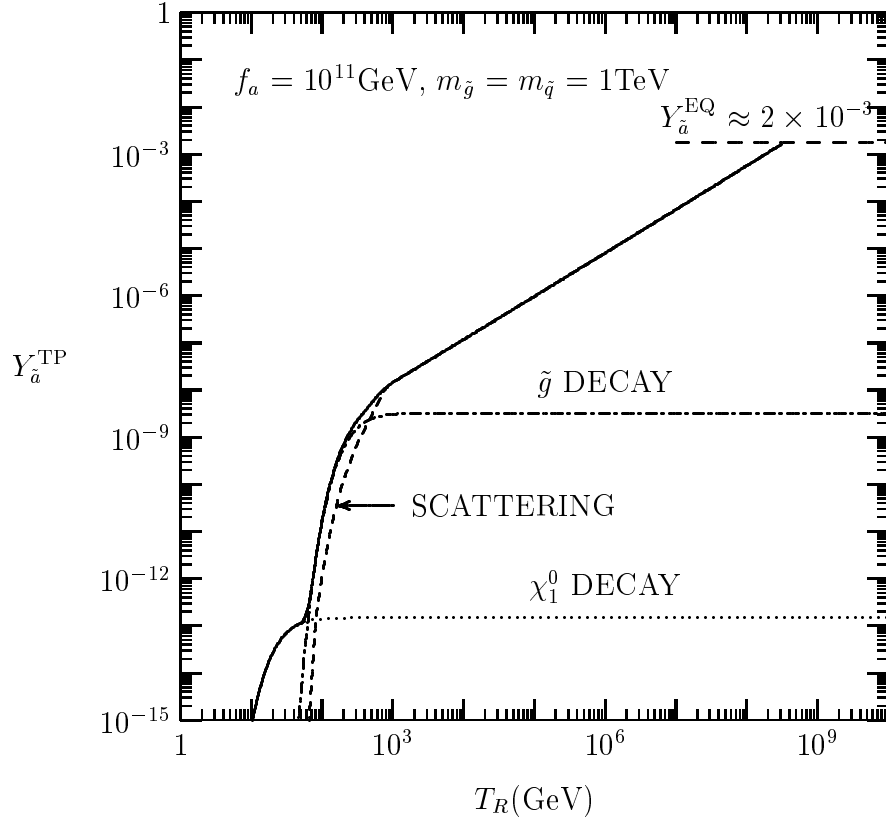


Fig. 1. $Y_{\tilde{a}}$ as a function of T_R for $F_a = 10^{11}$ GeV and $m_{\tilde{q}} = 1$ TeV.

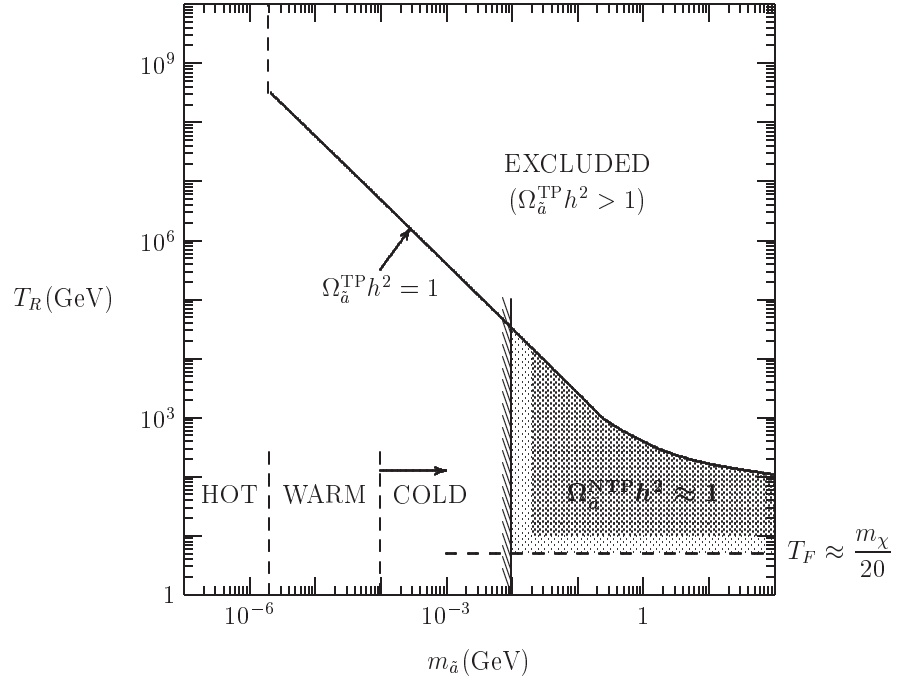


Fig. 2. Constraints on T_R and axino mass.